— Group 1 Report —

Impact of Sea Ice Production and Its Recent Reduction on Overturning and Material Circulation in the Okhotsk Sea and North Pacific

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1. Introduction

The Sea of Okhotsk is the southern limit of sea ice in the Northern Hemisphere (white shadings in Fig.1). This is because the cold pole in the Northern Hemisphere is located in the upwind region of the Sea of Okhotsk (colored contours in Fig.1). When sea ice is formed, most of the salt content is rejected from the ice and thus cold, saline and dense water is released into the ocean below. Since large amounts of sea ice are formed in the Sea of Okhotsk, the densest water on the surface of the North Pacific is produced there [Shcherbina et al. 2003]. Sinking of this dense water creates the vertical circulation (overturning) down to the intermediate depths (approx. 200 to 800 m deep) in the North Pacific. The Okhotsk thus plays a role as the pump of the North Pacific.

On the other hand, the Okhotsk is a sensitive area to global warming: the wintertime air temperature has significantly increased and sea ice extent has decreased by about 20% for the past three decades [Nakanowatari et al., 2007]. In this study, we propose that decrease of sea ice production caused the decline in dense water sinking, leading to the weakening of overturning in the North Pacific. The weakened overturning possibly affects the iron circulation, since the iron in the western North Pacific presumably originates from the dense (intermediate) water from the Okhotsk [Nishioka et al. 2007], further from the Amur River. Recent studies suggest that iron is a substantial factor in determining biological productivity. A possible scenario is discussed: current global warming, through sea ice reduction, might decrease the iron supply in the North Pacific as well as in the Okhotsk, thus reducing levels of biological productivity and fishery resources.

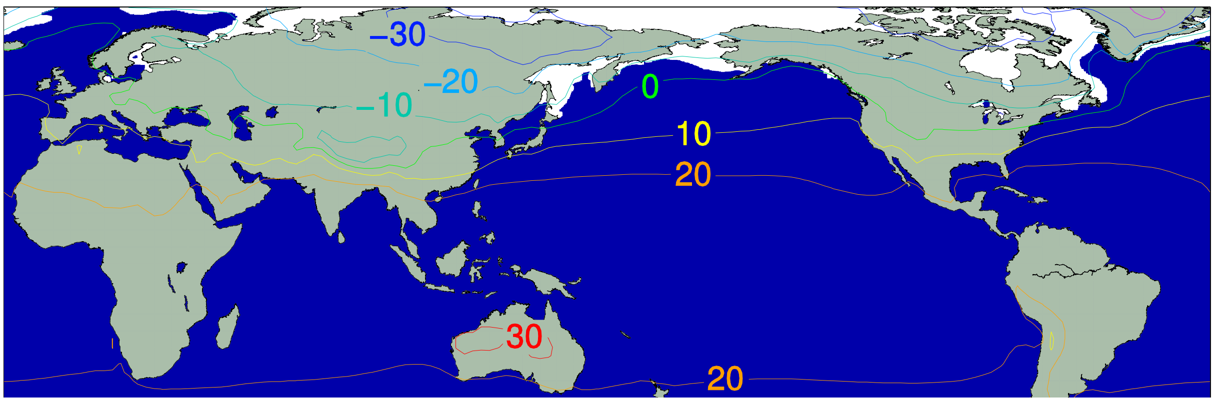

Figure 1: Climatology of global sea ice distribution (white) and surface air temperatures (isograms) in February. After from Nihashi et al. [2009].

2. ROLE OF THE OKHOTSK SEA

It is known that North Pacific Intermediate Water (NPIW), characterized by a salinity minimum at $26.8\sigma_\theta$, is a major water mass at the intermediate level of the North Pacific [e.g., Reid 1965]. Figure 2 shows the distribution of potential temperature and oxygen content on the $27.0\sigma_\theta$ isopycnal surface in the North Pacific. Cold and high oxygen water seems to originate from the Sea of Okhotsk. High CFC concentration [Warner et al. 1996] also originates from the Sea of Okhotsk. These distributions suggest that the ventilation source of intermediate water in the North Pacific, including NPIW, is the Sea of Okhotsk. Since large amounts of sea ice are formed in the Sea of Okhotsk, the densest water in the North Pacific (or to be exact, the densest water on the surface of the North Pacific) is produced there. Sinking of this dense water creates the overturning down to the intermediate depths in the North Pacific. The Okhotsk thus plays a role as the pump of the North Pacific.

Figure 3 shows the annual mean cumulative sea ice production calculated from sea ice information by satellite microwave and heat budget [Nihashi et al. 2009]. The northwestern shelf is found to be the far highest ice production region in the Sea of Okhotsk. Over the northwestern shelf, a large amount of sea ice is produced due to severe winds from northeastern Eurasia in winter. The sea ice production leads to production of cold,

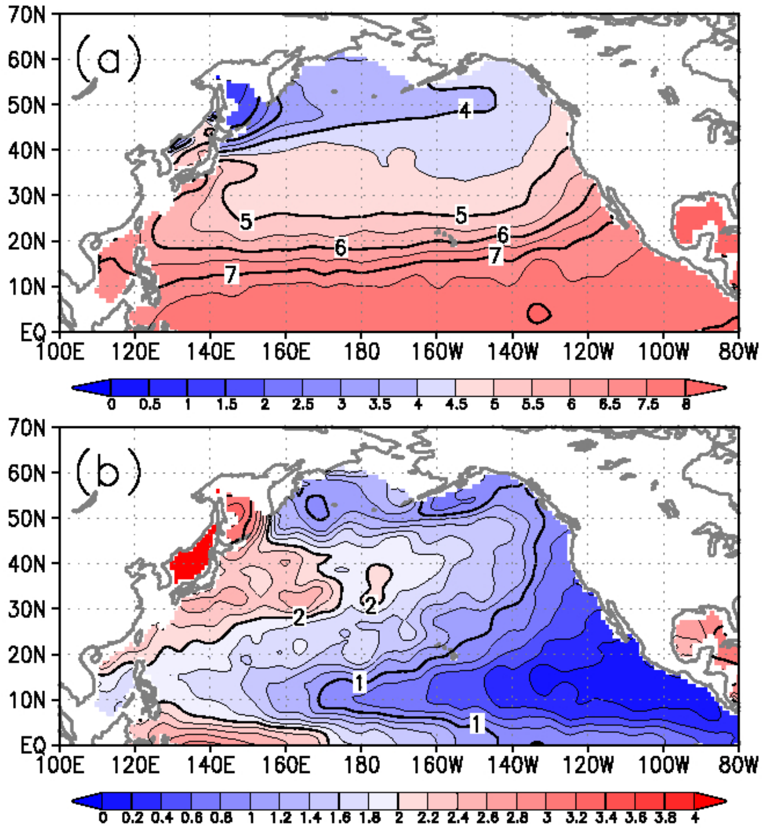

Figure 2: Horizontal distribution of (a) potential temperature (°C) and (b) dissolved oxygen content (mL/L) on the $27.0\sigma_\theta$ isopycnal surface in the North Pacific. These maps are based on World Ocean Atlas 1994 [Levitus et al. 1994].

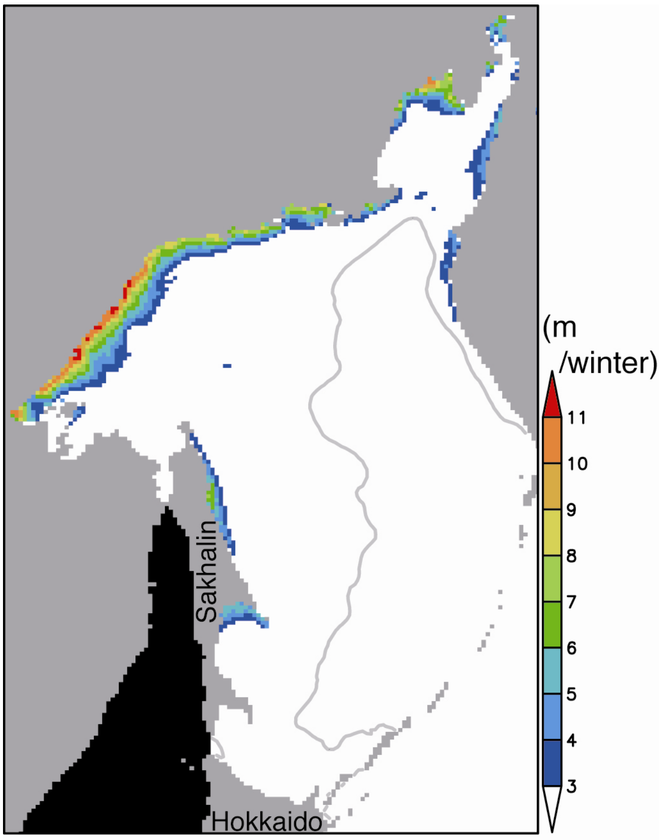

Figure 3: Annual mean cumulative sea ice production, represented by the ice thickness (cm). Estimation is based on the sea ice information from the satellite microwave and heat budget calculation. After Nihashi et al. [2009].

oxygen-rich dense shelf water (DSW) with densities of up to 27.0σ_θ [Shcherbina et al. 2003]. The DSW is transported southward into the intermediate layer in the southern Okhotsk Sea, and mixed with intermediate water coming from the North Pacific. This mixing forms the coldest, freshest and oxygen-richest water in the North Pacific in the density range of 26.8-27.4σ_θ [Talley 1991], which is called Okhotsk Sea Mode Water [Yasuda 1997] or Okhotsk Sea Intermediate Water (OSIW) [Itoh et al. 2003]. The signal of OSIW extends downward to 27.4σ_θ owing to diapycnal mixing caused by strong tidal currents around the Kuril Straits [Wong et al. 1998]. The OSIW outflows to the North Pacific through the Kuril Straits and then mixes with East Kamchatka Current Water, forming the Oyashio water. The Oyashio water reaches the confluence of the subtropical and subarctic gyres, and then part of the Oyashio water flows northeastward as the Subarctic Current (SAC), bounding the subarctic gyre on the south.

3. WARMING AND OXYGEN DECREASE TREND

For analyses of interannual variations in the Sea of Okhotsk and the North Pacific, we have used all available data of temperature, salinity and dissolved oxygen, taken from the World Ocean Database (WOD01), observational data obtained by the Japan-Russia-United States international joint study of the Sea of Okhotsk from 1998 to 2001, data archived by the Japan Oceanographic Data Center, and profiling float data up from 1999 to 2009. After the quality control, a gridded dataset of anomalies on isopycnal surfaces was then prepared.

Figures 4a and 4b show the potential temperature distribution on 26.9σ_θ surface in the Sea of Okhotsk, averaged over the two periods 1930-1980 and 1990-2009, respectively. The coldest water exists on the northwestern shelf and the cold water extends southward along the east Sakhalin shelf in both periods, suggesting that the intermediate water is ventilated through dense shelf water (DSW) due to high sea ice production in the northwestern shelf (Fig. 3). It is found that the temperature is obviously colder in 1930-1980. The difference of the two periods (Fig. 4c) is particularly large in the formation area of DSW and its pathway along the cyclonic gyre: the southward East Sakhalin Current and the subsequent eastward flow (Ohshima et al., 2004). These spatial features of Fig. 4c clearly confirm that the change (warming) of OSIW is caused by the decrease of DSW production.

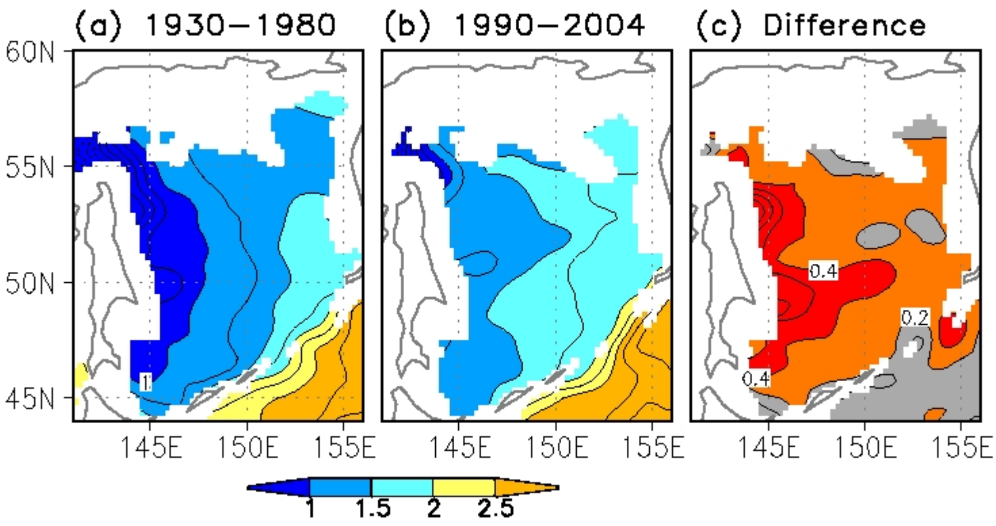

Figure 4: (a) potential temperature (℃) on the 26.9σ_θ isopycnal surface for 1930-1980, (b) same as (a) except for 1990-2009, (c) difference between (a) and (b).

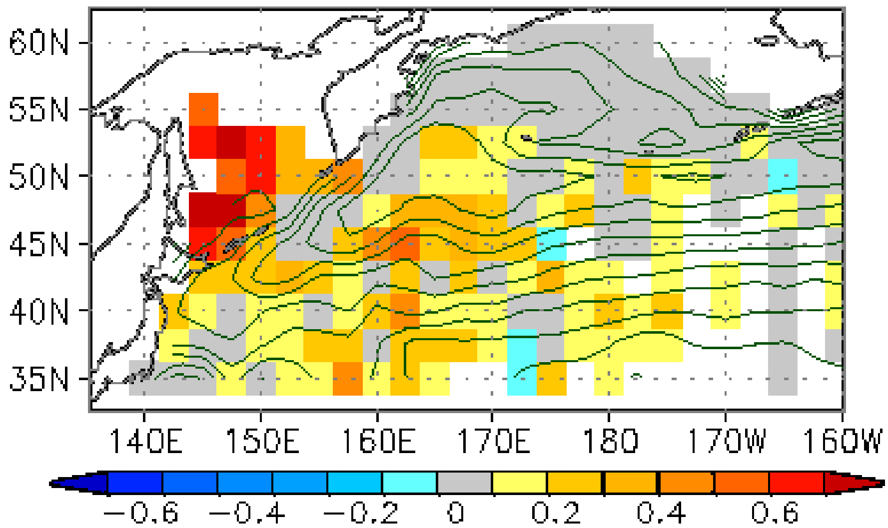

Figure 5: Linear trends (colors in°C/50-yr) of potential temperature anomalies at density 27.0σ_θ (approx. 300 – 500 m deep) from 1955-2004 in the North Pacific. Green contours indicate acceleration potential at 27.0σ_θ relative to 2000 dbar, derived from our dataset. Modified from Nakanowatari et al. [2007].

Figure 5 shows linear trend map of intermediate water temperature on the 27.0σ_θ isopycnal surface in the North Pacific including the Sea of Okhotsk for the past 50 years, 1955-2004. Significant warming trends are observed in the northwestern North Pacific and the Sea of Okhotsk. The warming trend in these regions is most prominent at density 27.0σ_θ, and the largest warming area exists in the western part (47.5°-55°N, 145°-147.5°E) of the Sea of Okhotsk with an average of 0.68°C/50-yr. The warming trend at 27.0σ_θ seems to extend along the pathway of the OSIW (see the acceleration potential at 27.0σ_θ, indicated by green contours in Figure 5). A significant warming trend is observed in the Oyashio and SAC regions, but not in the East Kamchatska Current region, i.e., upstream of the Sea of Okhotsk. Since the intermediate water masses in the Oyashio and SAC regions are largely affected by the OSIW [Yasuda 1997], these results indicate that the warming trend in the northwestern North Pacific may be caused by advection of warmed OSIW.

Figure 6 shows the time series of temperature and oxygen content anomalies at 27.0σ_θ, averaged over the Sea of Okhotsk. A positive and negative linear trend is the most significant feature for temperature and oxygen content, respectively. The temperature has increased by 0.62±0.18°C (significant at 99% confidence interval) during the past 50 years from 1955 through 2004. The oxygen has decreased by 0.58±0.34ml/l (significant at 95% confidence interval) for the past 45 years. The Oyashio and SAC regions also have the warming trend with the magnitude being about half of that for the Okhotsk and the oxygen decrease trend

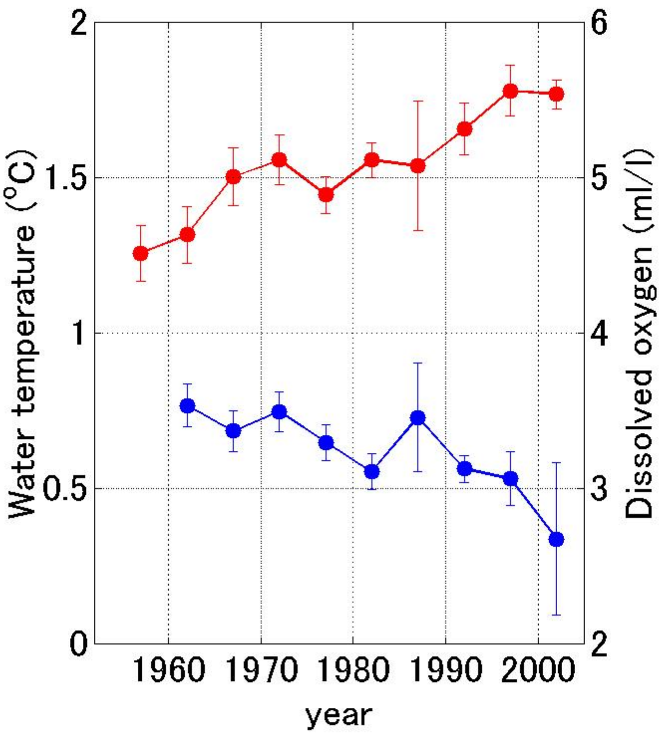

Figure 6: Time series of potential temperature (red line) and dissolved oxygen content (blue line) of the intermediate water at 27.0σ_θ , averaged over the Sea of Okhotsk, during the past 50 years. Closed circles show 5-yr average with errors at the 95% confidence interval for the averages. After Ohshima et al. [2008].

with the value less than that for the Okhotsk. Decreasing trend of oxygen in the Oyashio is consistent with Ono et al. [2001].

It is shown that warming and oxygen-decreasing trends in the intermediate water are most prominent in the Sea of Okhotsk. Moreover, these trends appear to extend to the northwestern North Pacific along the pathway of the water mass originating from the Sea of Okhotsk. These facts suggest that the trends in the northwestern North Pacific are due to preceding changes of water-mass properties in the Sea of Okhotsk. Intermediate water in the Sea of Okhotsk retains its cold and oxygen-rich properties by mixing with dense shelf water (DSW) associated with sea ice production in the coastal polynya of the northwestern shelf. The largest warming trend occurs in the western part of the Sea of Okhotsk (Figure 5), to which DSW is transported from the northwestern shelf [Fukamachi et al. 2004]. Therefore, we suppose that the main cause of the warming and oxygen-decreasing trends is the weakening of DSW production.

4. GLOBAL WARMING AND THE SEA OF OKHOTSK

DSW production is caused by sea ice production. Thus we examine the change of the sea ice extent or production in the Sea of Okhotsk. Over the last three decades since accurate observation by satellite became possible, sea ice extent in the Sea of Okhotsk has decreased by approximately 150,000 km^2, corresponding to about 10% of the entire area of the Sea of Okhotsk (blue line in Fig. 7). It has been also revealed that yearly variability of sea ice extent in the Sea of Okhotsk is highly correlated with that of surface air temperatures in the upwind region of the Okhotsk (red line in Fig. 7). Of particular note is that this temperature has risen by approximately 2.0°C over the past 50 years (2.0±1.4°C/50-yr, significant at 99% confidence level). This value of 2.0°C far exceeds the rate of average temperature increase

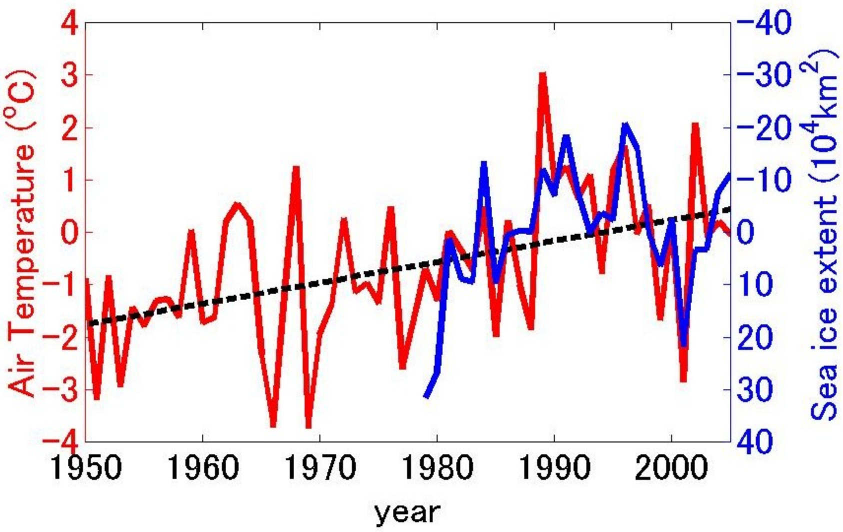

Figure 7: Time series of sea ice extent anomaly in the Sea of Okhotsk in February (blue line) and surface air temperatures anomaly in the upwind region (50°-65°N, 110°-140°E) of the Okhotsk (red line). Note that the scale of the sea ice extent is inverted (the axis on the right). Surface air temperatures are the mean values between October and March. Modified from Nakanowatari et al. [2007].

worldwide (0.65 °C over the past 50 years), thereby clearly indicating that the region is significantly affected by global warming. The correlation between this temperature and the sea ice extent (r=-0.61, significant at 95% confidence level) suggests that decreases in the sea ice preceded the beginning of satellite observations.

Although satellite measurements have only been available since the 1970's, visual observations at Hokkaido coast, located on the southern boundary of sea ice extent in the Sea of Okhotsk, show the decreasing trend of sea ice season length during the past 100 years [Aota 1999]. These trends of air temperature and sea ice season suggest that sea ice extent, accordingly sea ice production, has likely decreased during the past 50 years. During the current global warming, the surface air temperature anomaly in autumn and winter is particularly large over northeastern Eurasia [Serreze et al. 2000]. The DSW production area of the northwestern shelf in the Sea of Okhotsk is located where the winter monsoon from northeastern Eurasia directly transports cold air masses. Therefore, intermediate water in the Sea of Okhotsk which is ventilated through DSW may be sensitive to the global warming.

5. POSSIBLE SCENARIO

In a nutshell, the Sea of Okhotsk is highly sensitive to global warming: over the past 50 years, the level of sea ice production has decreased and the amount of dense water sinking has thus declined, thereby weakening the overturning in the North Pacific scale. To put it simply, the recent global warming has weakened the Sea of Okhotsk's workings as a pump.

Recent studies suggest that OSIW has a significant role in material circulation of the intermediate layer in the North Pacific. Hansell et al. [2002] indicated that dissolved organic carbons in NPIW originate from the Sea of Okhotsk. Nakatsuka et al. [2004] showed that large amounts of dissolved and particulate organic carbons are exported from the highly productive northwestern shelf into the intermediate layer in the Sea of Okhotsk through the outflow of DSW. Moreover, recent observational data show that in the northwestern North Pacific, iron may come from the intermediate water of the Sea of Okhotsk [Nishioka et al. 2007]. Iron is an essential micronutrient for phytoplankton and thus considered an important factor in determining biological productivity. It has been recently revealed that when dense shelf water sinks to the intermediate layer in the Sea of Okhotsk, iron is also brought to this layer (Fig. 8). This iron is considered to originate from the Amur River. We hypothesize that this iron is also supplied to the western area of the North Pacific and supports high biological productivity there [Nishioka et al. 2007]. If that is the case, it is also possible to suggest that if global warming weakens sea ice production in the Sea of Okhotsk, iron supplies will decrease in the North Pacific as well as in the Sea of Okhotsk, thus reducing levels of biological productivity and fishery resources (Fig. 8).

Flow chart of Figure 8 shows a possible scenario. Because the Sea of Okhotsk is a sensitive area to the current global warming, production of sea ice and dense shelf water in the northwestern shelf has decreased during the past 50 years. This possibly causes a decrease in supply of iron in the intermediate layer in the Sea of Okhotsk and further in the North Pacific. Finally, this might induce the decrease in primary biological production, fishery resources, and capacity of CO_2 absorption.

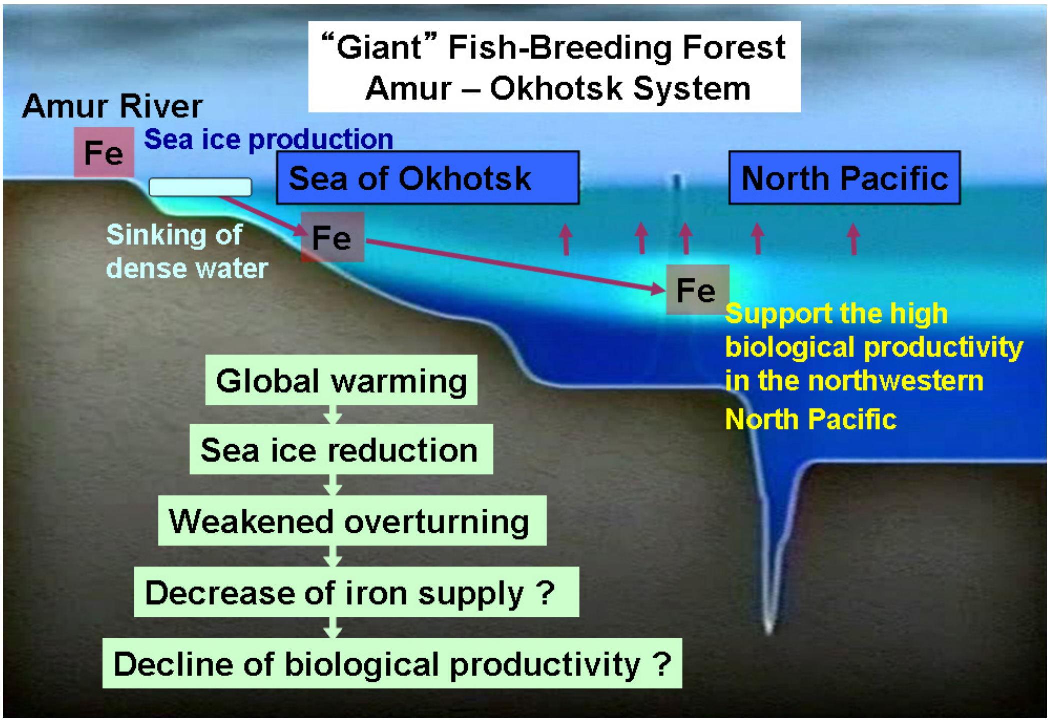

Figure 8: Schematics of iron circulation through the Amur-Okhotsk system and the effects of global warming on it.

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